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World water tower: An atmospheric perspective

Xiangde Xu,[1] Chungu Lu,[2] Xiaohui Shi,[1] and Shouting Gao[3]

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[1] A large amount of water is stored in the world's highest and largest plateau, the Tibetan Plateau, in the forms of glaciers, snowpacks, lakes, and rivers. It is vital to understand where these waters come from and whether the supply to these water resources has been experiencing any changes during recent global warming. Here we show the maintenance of water content in the atmosphere over the Tibetan Plateau, the atmospheric circulations and transports of water vapor to this part of the world, and the trend of the water vapor supply. The Tibetan Plateau serves as a role of "the world water tower", and its land-ocean-atmosphere interaction provides a profound impact on the global natural and climate environment. The analyses of a half-century time series of atmospheric water vapor, precipitation, and surface temperature indicate that the atmospheric supply to this water tower presents an increasing trend under recent global warming condition. **Citation:** Xu, X., C. Lu, X. Shi, and S. Gao (2008), World water tower: An atmospheric perspective, *Geophys. Res. Lett.*, *35*, L20815, doi:10.1029/2008GL035867.

1. Introduction

[2] The Tibetan Plateau has always been referred to as the "roof of the world." Covering about a quarter of China's total land area, the average elevation of this land is over 4000 m. This elevated land plays an important role in global natural and climate environment, and results in the most pronounced monsoon circulation on Earth. The Tibetan Plateau is also a natural museum for mid- and low-latitude glaciers, snowpacks, frozen land, and plateau vegetation. Thousands of lakes and glaciers are scattered across this vast region. The area of lakes and the snow/ice storage in this region account, respectively, for 52% and 80% of total lake area and glaciers of entire China. The water resource from these lakes, glaciers, and rivers over the plateau and its immediate downstream regions (including Yunnan, Guanxi, Sichuang, and Qinghai provinces) accounts for about 47% of total surface water resources in China [*Tung*, 2002; *Ding*, 2002]. These highland waters are carried down to the surrounding regions via a large network of streams and groundwater aquifers. It is here that many of China and Asia's major rivers originate such as the Yangtze, Yellow, Indus, Mekong, and Ganges Rivers, comprising the largest river runoff from any single location in the world [*Ding*, 2002; *Lu et al.*, 2005]. These waters have been sustaining life, agricultural, and industrial water usage for nearly 40% of the world's population, including China and India, the two emerging economical powers [*United Nations Environment Programme* (*UNEP*), 2007]. The upper-level atmospheric moisture transport also affects the entire global natural and climate environment. Combining all these facts, it is not an overstatement to call the Tibetan Plateau "the global water tower." It is vital to understand the atmospheric roles in maintaining of these waters over the Tibetan Plateau, the atmospheric circulations and transports of water vapor to this part of the world, and the trend of the water vapor supply during recent global warming.

2. Characteristics of Water Vapor Over the Plateau

[3] To maintain this water tower transporting water to the surrounding areas, there must be a sustainable supply. Obviously, the melting of glaciers and atmospheric precipitation are the continuous supply for the ceaseless water runoff. While a lot of mountain glaciers and snowpacks have been accumulated through an epic time scale accompanied by a dynamic evolution of the formation of the plateau, the atmospheric precipitation has been the ultimate supply to this water storage [*Lu et al.*, 2005; *Davis et al.*, 2005; *Duan et al.*, 2006]. Furthermore, for annual river discharge over the Tibetan Plateau, precipitation contributes the major amount for the outflow waters. *Lu et al.* [2005] showed that glacial meltwater constitutes about 7.2% of total river discharge from the Tibetan Plateau in China. The questions are then what the characterization of the atmosphere water vapor over the Tibetan Plateau is, where this water vapor comes from, and what a special role the plateau's geographic feature plays in this ocean-land-atmospheric interaction. Figure 1a shows a horizontal distribution of 59-year averaged annual mean water vapor content (black contours) between a 500–300 hPa atmospheric layer (the red dashed line marks the Tibetan Plateau). The data used in this calculation is from the U.S. National Center for Atmospheric Research and the National Centers for Environmental Prediction's 59-year reanalysis (1948–2006). One can see from this calculation that the atmosphere presents a distinctive pool of water vapor maximum right above the Tibetan Plateau. Further calculation of a 59-year mean moisture distribution for summer in the vertical cross sections along a meridional direction (Figure 1b: averaged for 80°E–110°E) and along a latitudinal direction (Figure 1c: averaged for 27.5°N–35°N) shows that the elevated lands (including the Tibetan Plateau and North American Rockies, shaded in dark brown) effectively push moisture up. Due to its significant rise-up in altitude and extensive coverage spatially, the Tibetan Plateau seems to exert an effect of atmospheric water

[1]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China.
[2]Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.
[3]Institute of Atmospheric Physics, Chinese Academy of Science, Beijing, China.

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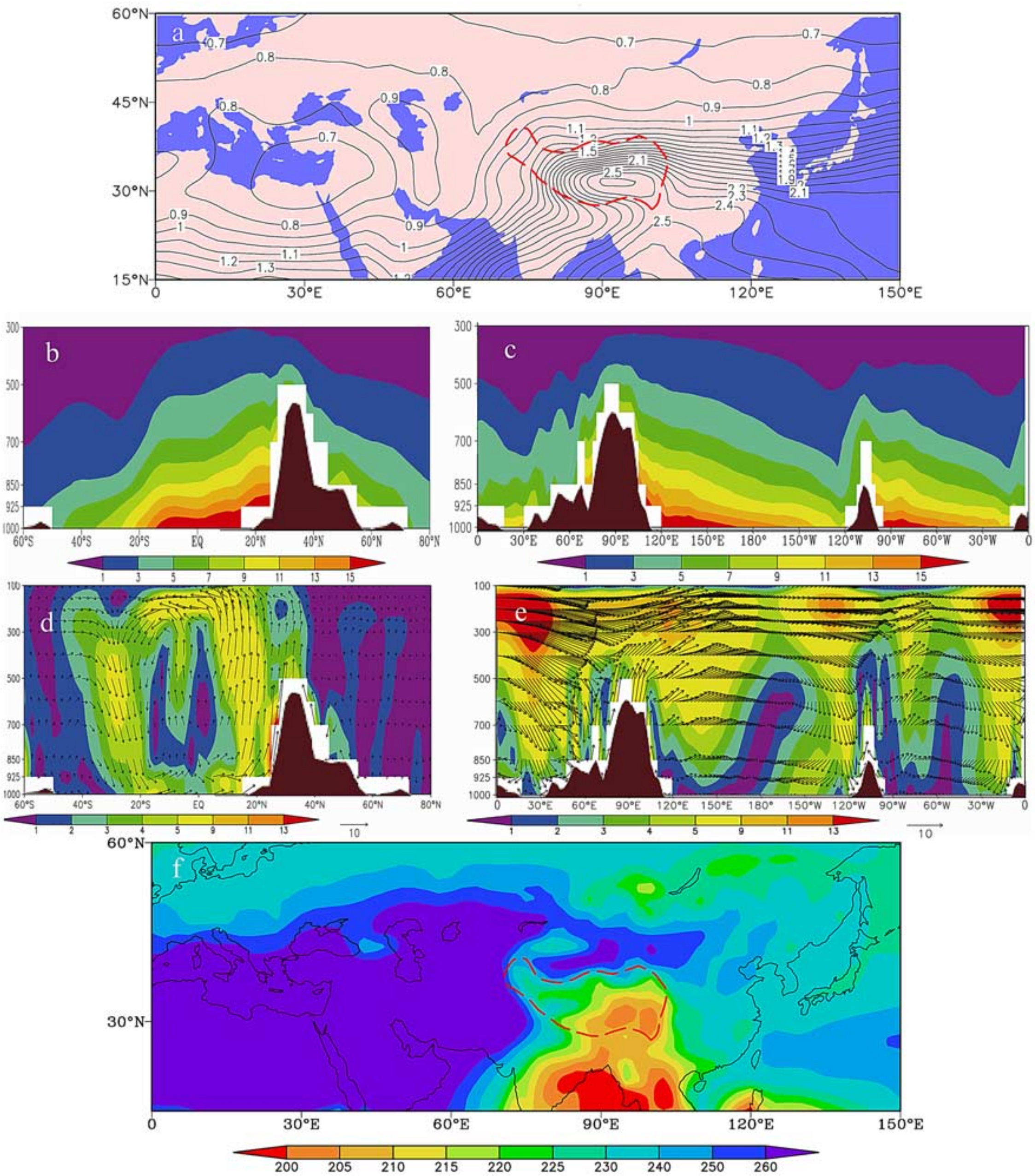

Figure 1. Horizontal distribution of 59-year (1948–2006) averaged (a) annual mean column water vapor content (contour, in kg m^{-2}) between a 500–300 hPa atmospheric layer; (b) vertical cross sectional distribution of mean summer specific humidity (in unit: gkg^{-1}) in the meridional direction (averaged for 80°E–110°E); (c) same as Figure 1b, except in the latitudinal direction (averaged for 27.5°N–35°N); (d) wind vector and speed (color-shaded, in unit: ms^{-1}) in the meridional vertical cross section (averaged for 80°E–110°E); (e) same as Figure 1d, except in the latitudinal vertical cross section (averaged for 27.5°N–35°N); and (f) averaged summer OLR (color shaded, in Kelvin) during 1975–2006. Dark brown-shaded in Figures 1b–1e are topography.

characteristics on a global scale. On its east side, the moisture slopes down all the way across the Pacific and to the foot of the North American Rockies. On its south side, the moisture slopes up from Southern Hemispheric oceans, crosses the Equator and into the Northern Hemisphere, and climbs up the Tibetan Plateau. These results provide a more complete picture of the Tibetan water tower: in the atmosphere above, a pool of concentrated water vapor serves in the role of "water-supply tank"; at the surface, glaciers, snowpacks, and lakes serve as a "water-storage pool"; and all the rivers connecting to the plateau function as "water pipelines" that transport water away. The upper atmosphere channels in and out moisture, which affect the entire world's water environment. We verified this result using a half-century's (1957–2006) upper-air radiosonde observations in China, which also indicates a water vapor

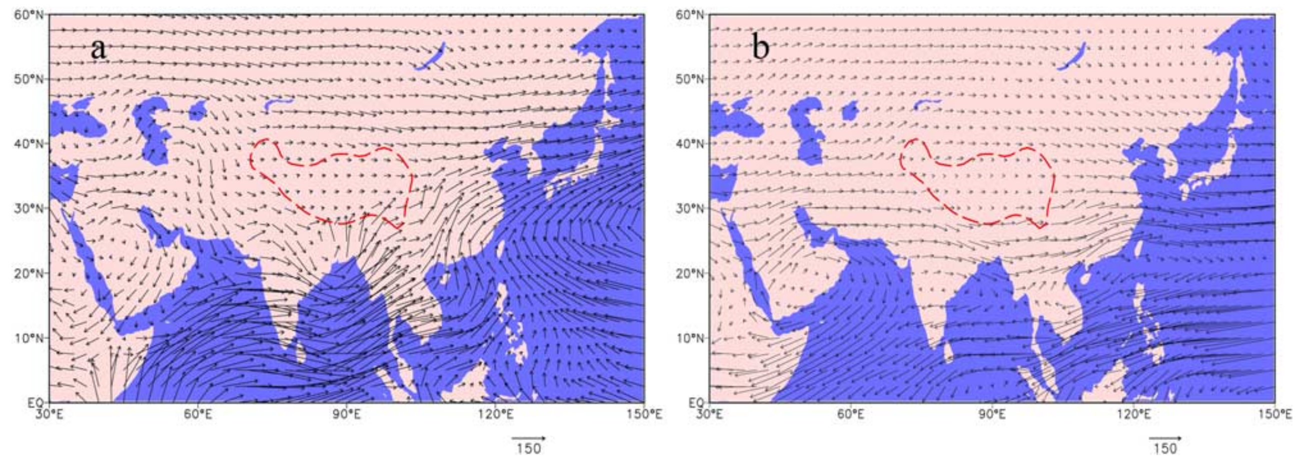

Figure 2. Horizontal distribution of 59-year averaged column water vapor flux (vectors, in kg m^{-1} s^{-1}) for (a) summer and (b) winter, respectively.

maximum over the Tibetan Plateau in atmospheric columns above 500 hPa (see Figure S1 of the auxiliary material).[1]

3. Atmospheric Circulations and Water Vapor Transports

[4] Clearly, the unique geological feature of the plateau is responsible for this global moist distribution. To understand the dynamics and transport of moisture in the atmosphere, we calculated 59-year mean atmospheric circulations in the above two vertical sections (Figures 1d and 1e) and mean horizontal distribution of whole column water-vapor flux (Figure 2). Because of a strong contrast in the thermal property between land and ocean, the seasonal change results in a cross-south-north hemispherical monsoonal circulation. In the summer half of a year (May–October), the Tibetan Plateau acts as a strong "dynamic pump" [*Wu and Zhang*, 1998] continuously attracts moist air from the low-latitude oceans (Figures 1d and 2a). This moisture is concentrated at low-levels and transported by lower branch of atmospheric flows [*Bai and Xu*, 2004]. However, when reaching the plateau, a portion of these flows rises along the south side of the plateau, and causes frequent convections and precipitations [*Xu et al.*, 2003]. Water is transported back via surface rivers and upper-level returning flows. The other portion of water vapors is blocked by the plateau and then deflected to the east side of it and caught by the prevailing westerly wind (Figure 1e). This westerly wind transports abundant moisture to the eastern China and Asia (Figure 2a). Again, surface rivers transport downwind precipitation water back to the oceans, but at the mid and upper atmosphere, the water tower presents a "re-channel function" which constitutes a planetary-scale circulation across the east and west hemispheres. The above cross-south-north hemispheric meridional circulation and cross-east-west-hemispheric latitudinal circulation are related to the plateau's thermal and mechanical driving forcing, noticing that the upward motion starts over the Tibetan Plateau (Figures 1d and 1e). The combined oceans, the plateau, surface glacier, lake, river systems, and upper-level atmospheric circulations depict a complete planetary-scale land-ocean-atmosphere water cycle on Earth. In the winter half of a year (Figure 2b, November–April), the monsoonal flows in the low-latitude oceans reverse. A persistent anticyclone occurs over the Arabian Sea along the coast of Somalia, which possesses a southwesterly flow on its northwest flank. This flow feeds more moisture into the subtropical jet coming from the Mediterranean. The further moistened westerly jet continues to transport water vapor into the plateau region and downstream region during the winter.

4. Plateau Cloud System and Precipitation

[5] The Tibetan Plateau is not only a place favorable for moisture convergence, it also renders the ideal condition for moist air to condense and develop into plateau convective clouds due to its elevated land surface and strong radiative heating. Figure 1d shows the averaged summer Outgoing Long-wave Radiation (OLR) measured by satellite during 1975–2005. The summer OLR is a proxy for convective clouds. The low-value color-shaded region over the Tibetan Plateau indicates a high occurrence of convective clouds. Precipitation in the Tibetan Plateau is mainly due to these convective cloud systems (an example can be found in Figure S2).

[6] Further analyses of a half-century observational data obtained from 9 upper-air-sounding sites and 50 surface weather stations around the Tibetan region result in a negative correlation between summer OLR and water vapor content, but a positive correlation between water vapor content and precipitation (Figure S3). The averaged occurrence of cumulonimbus in the Tibetan Plateau is about 345 times/year. This number is about 2.5 times higher than its surrounding area [*Xu et al.*, 2002; *Dai*, 1990; *Flohn*, 1968]. The frequent occurrence of convective clouds and precipitation indicates a rapid removal of water vapor from the Tibetan Plateau water-supply tank. The new moist air must fill in immediately, following the fact that this water vapor maximum in Figure 1a is presented as a climatologically persistent signal. This picture thus provides a mechanism of "constant refill" of the water tower by the atmosphere. The winter precipitations (close to 40% of total

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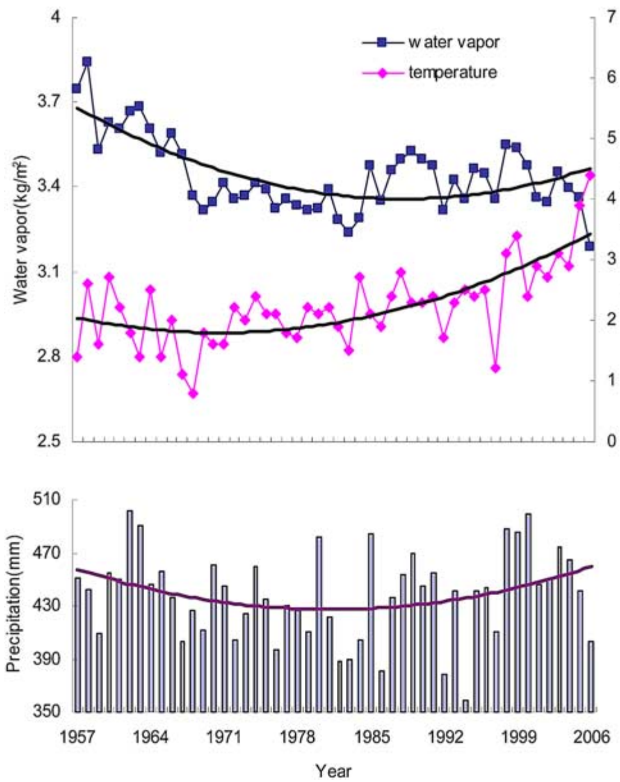

Figure 3. A 50-year time series (1957–2006) of annual mean column water vapor content (blue dotted curve), annual mean surface temperature (pink-dotted curve), and annual total precipitation (blue bars) in the Tibetan region. The solid curves are the fitting to these data.

annual precipitation [*Liu and Yin*, 2001]) will be stored as snowpacks, which provide latent water sources for summer river discharge. The summer precipitations (about 60% of total annual precipitation [*Liu and Yin*, 2001]) will either contribute directly to the surface runoff or deposit on high mountains, depending on the variability of near-surface temperature. Because the plateau also deflects a large portion of moisture to the east (Figure 2), downstream precipitation can be an important reinforcement for large river discharge, particularly for China.

5. Trend of Atmospheric Water Supply to the Plateau Water Tower

[7] The present and future conditions of the Tibetan water tower concern not only a sustainable socio-economical development, but also the survivability reality for close to 40% of the world's population [*UNEP*, 2007]. Therefore, changes in this water tower have long been the focus of scientists worldwide. It has been reported recently that a rapid melting of glaciers in many large mountains in the Tibetan Plateau region is occurring, possibly in response to the global warming [*Pearce*, 1999; *Liu and Chen*, 2000; *Oku et al.*, 2006]. This implies a rapid reduction of water storage in the water tower. From the atmospheric perspective, one of the important questions that need to be addressed is whether the atmosphere supply to the Tibetan water tower has experienced any change under the current warming conditions.

[8] To answer this question, we computed a half-century (1957–2006) time series of total column of water vapor, surface temperature, and precipitation amount from historical records for the Tibetan region (averaged from 9 upper-air sounding stations and 50 surface observational stations: Figure S4). In Figure 3, averaged annual variations of total water vapor content and surface temperature are plotted as the dotted curves, while fittings to these data are plotted as solid curves. The recent warming in the plateau started in the early 1970's, while the water vapor content showed an upward trend in the early 1980's and continues to the present time. The same patterns are found in the averaged annual precipitation (the blue bars in the lower panel of Figure 3). The increase of water vapor over the Tibetan Plateau may be due to following two possible mechanisms: 1) intensification of monsoonal circulation leads to a increased water vapor transport; 2) the increase of surface air temperature over the Tibetan Plateau causes that the air above it can hold more moisture.

[9] These results suggest several possible consequences under the current warming scenario. First, owing to the combined effect of the rapid melting of glaciers and increased precipitation in the Tibetan Plateau due to global warming, the downstream transport of water from the Tibetan water tower would increase in volume. This may cause an increase in the severe flooding problems for countries along the major rivers that discharge this water. Although in China, the flooding of major rivers is typically due to downstream precipitations, the effect of Tibetan water tower runoff may aggravate the problem, causing an increase in the flooding frequency and severity in recent years [*Huang et al.*, 2003]. It was also reported that winter temperature anomaly over the northeastern Tibetan Plateau can be an important indicator for the drought and flooding conditions over India [*Bansod et al.*, 2003]. Second, the increase of surface temperature and precipitation may result in a change in the ecosystem over the plateau region. Finally, although the rapid retreat of glaciers over the plateau's mountains may pose a serious socio-economical issue for the water resources that feed 40% of the world's population, the atmosphere would present a somewhat positive response to the problem. That is, the increased atmospheric supply may alleviate the problem of rapid depletion of water resources arising from the melting of glaciers.

6. Conclusions

[10] In this study, a persistent pool of water vapor maximum is found over the Tibetan Plateau between a layer of 500–300 hPa in the atmosphere. Although the plateau's elevated topography contributes to this pool of moisture, the low-latitude oceans are the source for this moisture, which is transported by atmospheric flows from tropical oceans to the plateau region. This land-ocean-atmosphere interaction presents a complete picture of water cycles on Earth. The finding of atmospheric water vapor maximum also provides a link for the source of rich surface water storage over the Tibetan Plateau. Furthermore, the calculations for water vapor distribution and atmospheric circulation in the zonal and meridional vertical sections indicate a global-scale influence by the Tibetan Plateau, thus supporting the

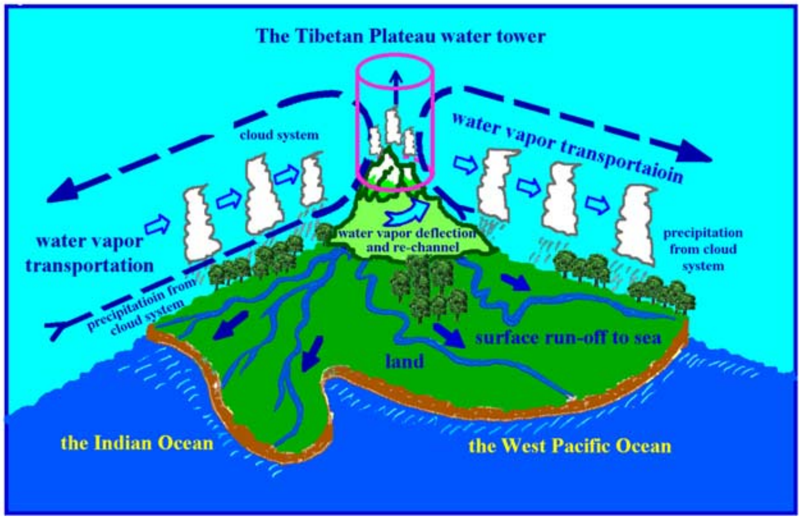

Figure 4. Schematic diagram of the Tibetan Plateau as a role in land-ocean-atmosphere interaction and hydrological cycle.

concept of "world water tower." That is, in the atmosphere above, a pool of concentrated water vapor takes on the role of a "water-supply tank"; at the surface, glaciers, snowpacks, and lakes serve as a "water-storage pool"; and all the rivers connecting to the plateau function as "water pipelines" that transport water away. The atmosphere also provides upper-level channels that transport water vapor in and out of the Tibetan Plateau region.

[11] Strong surface radiative heating and topographic lifting provide favorable conditions for convection, which often results in precipitation. The frequent precipitation is crucial as a "constant refill" mechanism for the world water tower.

[12] Based on the analyses of water vapor, clouds, precipitation, and atmospheric circulations, a schematic diagram (Figure 4) can be constructed for the concept of "the world water tower" and its hydrological function for its surrounding areas.

[13] Finally, an analysis of a half-century time series of atmospheric water vapor content, precipitation, and surface temperature indicates that the atmospheric supply to the world water tower presents an increasing trend under recent global warming conditions. This finding implies that on one hand, the increase of water vapor content and precipitation over the Tibetan Plateau may alleviate the rapid depletion of glaciers and snowpacks due to the global warming. On the other hand, it may alter the ecosystem over the Tibetan Plateau region and may also increase severe flooding and related problems for the downstream regions.

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References

Bai, J., and X. Xu (2004), Atmospheric hydrological budget with its effects over Tibetan Plateau, *J. Geogr. Sci.*, *14*, 81–86.

Bansod, S. D., Z. Yin, Z. Lin, and X. Zhang (2003), Thermal field over Tibetan Plateau and Indian summer monsoon rainfall, *Int. J. Climatol.*, *23*, 1589–1605.

Dai, J. (1990), *Tibetan Plateau Climate* (in Chinese), 368 pp., China Meteorological, Beijing.

Davis, M. E., L. G. Thompson, T. Yao, and N. Wang (2005), Forcing of the Asian monsoon on the Tibetan Plateau: Evidence from high-resolution ice core and tropical coral records, *J. Geophys. Res.*, *110*, D04101, doi:10.1029/2004JD004933.

Ding, Y. (2002), The outlook of environmental changes in western China, in *Assessment of Environment Evolution of Western China* (in Chinese), pp. 147–170, Science, Beijing.

Duan, K., T. Yao, and L. G. Thompson (2006), Response of monsoon precipitation in the Himalayas to global warming, *J. Geophys. Res.*, *111*, D19110, doi:10.1029/2006JD007084.

Flohn, H. (1968), Contribution to a meteorology of the Tibetan Plateau on the formation of Asia monsoon circulation, *Atmos. Sci. Pap. 130*, Colo. State Univ., Fort Collins.

Huang, R., et al. (2003), Studies on the relationship between the severe climate disasters in China and the east Asia climate system (in Chinese), *Chin. J. Atmos. Sci.*, *27*(4), 770–787.

Liu, X., and B. Chen (2000), Climate warming in the Tibetan Plateau during recent decades, *Int. J. Climatol.*, *20*, 1729–1742.

Liu, X., and Z. Yin (2001), Spatial and temporal variation of summer precipitation over the eastern Tibetan Plateau and the North Atlantic Oscillation, *J. Clim.*, *14*, 2896–2909.

Lu, C., G. Yu, and G. Xie (2005), Tibetan Plateau serves as a water tower, *IEEE Trans. Geosci. Remote Sens.*, *5*, 3120–3123.

Pearce, F. (1999), Flooded out, *New Sci.*, *2189*, 18.

Oku, Y., H. Ishikawa, S. Haginoya, and Y. Ma (2006), Recent trends in land surface temperature on the Tibetan Plateau, *J. Clim.*, *15*, 2995–3003.

Tung, M. (2002), The impact of Tibetan Plateau on the environment evolution of western China, in *Assessment of Environment Evolution of Western China* (in Chinese), pp. 147–170, Science, Beijing.

United Nations Environment Programme (UNEP) (2007), *Global Outlook for Ice and Snow*, edited by J. Eamer, A. Hugo, and P. Prestrud, U. N. Environ. Programme, Nairobi. (Available at http://www.unep.org/geo/ice_snow)

Wu, G., and Y. Zhang (1998), Tibetan Plateau forcing and the Asian Monsoon onset over south Asia and South China Sea, *Mon. Weather Rev.*, *126*, 913–927.

Xu, X., et al. (2002), A comprehensive physical pattern of land-air dynamics and thermal structure on the Qinghai-Xizang Plateau, *Sci. China, Ser. D*, *45*, 577–594.

Xu, X., Q. Miao, and J. Wang (2003), The water vapor transport model at the regional boundary during the Meiyu period, *Adv. Atmos. Sci.*, *20*, 333–342.

C. Lu, Earth System Research Laboratory, NOAA, 325 Broadway, Boulder, CO 80305, USA. (chungu.lu@noaa.gov)

S. Gao, Institute of Atmospheric Physics, Chinese Academy of Science, Huayanbeili #40 Building, Chaoyang District, Beijing 100029, China.

X. Shi and X. Xu, State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, 46 Zhong-Guan-Cun South Street, Beijing 10081, China.